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7. Author(s) Stanley A. Klein, Ph.D.		8. Performing Organization Rept. No.
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16. Abstract (Limit: 200 words)

a. Models of human vision were applied to image compression and image fidelity for both static and dynamic images.

. The role of the human observer in JPEG compression was clarified. The human observer's visual information capacity was calculated to be about 20 bits/min^2, substantially higher than previous estimates.

. New formulas were developed for the Fourier transform of JPEG basis functions, connecting JPEG quantization matrices to the human observer's contrast sensitivity function.

. Crawford masking was used to measure the visibility of lines and edges following abrupt luminance changes. The high frame rates produced higher temporal resolution than previous studies. A striking asymmetry between light and dark lines was found.

b. A robust test-pedestal framework was developed for modeling spatio-temporal vision with fewer assumptions than previous models. In this framework motion processing and hyperacuity thresholds are directly related to contrast processing.

c. A number of studies on motion processing developed new limits on the human visual system's capabilities.

d. In order to connect psychophysics results to underlying physiological mechanisms new techniques were developed for nonlinear analysis and source localization of visual evoked potentials and other biopotentials.

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Final report for AFOSR-89-0238 **October 8, 1992**

Title: Spatio-temporal Masking: Hyperacuity and Local Adaptation.
Period covered: January 1, 1989 - July 31, 1992

Objectives of the research effort.

a. Apply models of human vision to several areas of applied image processing (image compression and image quality), such as high definition television and teleconferencing.

b. Develop robust "ideal-observer" methods for modeling spatio-temporal vision with fewer assumptions than previous models. The test-pedestal framework for spatio-temporal interactions uses the same test pattern with multiple pedestals in different phase relationships to learn about the properties of the underlying mechanisms. We seek to connect motion processing to contrast processing.

c. Discover the limits of spatial processing while the stimuli are rapidly moving, flickering or jittering. Develop models to account for this data.

d. Connect our psychophysics research to the underlying physiological mechanisms. In this regard we have found that new techniques are needed to learn about nonlinear visual processing so we are improving methods for the nonlinear analysis and source localization of visual evoked potentials and other biopotentials.

Overview of this final report.

The past three years have been very productive for our research group. Based on AFOSR support we have 21 papers either published or submitted for publication (excluding research supported solely by NIH). I am including with this report a copy of those papers that were not previously sent (or those for which preliminary versions were sent). In this report I will refer to some of these papers. I will use the notation "#4" to mean paper number 4 in the list of references at the end of this report. If I were to summarize the work done on each paper this document would become excessively lengthy. Instead, this summary will provide a short summary of our AFOSR supported activities in the following four areas: 1) A brief summary of our research on connecting the insights from human vision to applied topics (image compression and image quality). 2) A summary of our work on vernier acuity to show our approach to modeling. An outgrowth of this research is our collaboration with other Berkeley faculty to develop a user-friendly environment for modeling vision. 3) A brief summary of our research on elaborating the mechanisms of motion processing. 4) A summary of our work measuring biopotentials. In order to connect our psychophysical data and models to underlying physiological mechanisms we have executed several visual evoked potential studies and have developed new methodologies for studying nonlinear physiological processing.

The full details for much of our AFOSR supported research can be found in the published articles that are either enclosed with this report or have been sent previously. Some of this completed research will be reviewed briefly in this report. Abstracts of some of our <u>unpublished</u> AFOSR supported work will be included in this final report.

1) Image compression and image quality. Eight of the papers that have been written during this grant period are connected with image compression and the assessment of image quality [#1, #2, #4, #5, #7, #11, #14, #18]. The field of image compression is growing very rapidly because of the arrival of HDTV, teleconferencing and picture phone and also because of developing standards by committees such as JPEG and MPEG. The standards developed by JPEG and MPEG are ideal for the vision research community. The quantization algorithm is based squarely on properties of the human visual system. Much more information from researchers in human vision is needed on how to do context dependent image compression and image quality evaluation. That is, different types of image degradation will be more or less visible depending on the local context of the image. This is the topic of visual masking. One of the directions of both our basic research and our applied research is to show that the calculation of masking magnitude is more difficult than commonly believed. We are able to demonstrate situations with strong pedestals in both space and time where the masking is minimal. Based on these results we have calculated that the human visual system is able to take in much more information than is transmitted by normal compression schemes. We believe that our research is relevant whenever the goal is to achieve perceptually lossless compression. The best summary of our research for static images is our recent SPIE paper [#18].

One area of special interest involves temporal masking. We are interested in how much compression is possible when there is a sudden change in scenes. When a new scene appears in an image sequence a tremendous amount of new information is needed to represent the scene. We want to learn what aspects of the sudden scene change are not visible to the human observer immediately. Amnon Silverstein and Qingmin Hu will be doing their doctoral dissertations in this area. The following abstract shows one of our directions in his research.

LINE DETECTION UNDER TEMPORAL MASKING (ARVO 1992)

The Crawford masking flash-on-flash paradigm was employed to study the effect of temporal masking on the detection of a thin line. We wanted to use finer temporal resolution (5 msec) than previous studies. The adapting background was 90 cd/m^2. The masker was a uniform square field of 6 degrees with a luminance increment of 50 cd/m^2. The masking field was flashed on for 500 msec. The target was a 2 minute wide vertical line which was briefly (5 msec) flashed on at the center of the masking field. Detection thresholds were measured at different SOAs of the masking flash with a sampling interval of 5 msec. Data were obtained by the method of constant stimuli with multiple responses. Three major effects were observed: (1)The masking of a thin line by a uniform field had a very short time course: about 25 msec full width at half maximum. (2)The psychometric function for the thin line detection under temporal masking was steeper than the no-masking condition. The exponent of the psychometric (transducer) function relating d' to contrast was 2.49 ± 0.25 and 1.79 ± 0.16 for the mask and no-mask conditions. (3) Crawford masking functions were obtained for a 2 min line and a 4 min line. The detection thresholds of the 2 min line were almost double the 4 min line thresholds in the no-mask case and only about 10% higher with the masker. This is consistent with the finding that high spatial frequency detectors do not respond well to the luminance transient. (4) One of our most interesting findings is the strong asymmetry between light and dark test lines, indicating temporal delays in the gain control mechanism.

Another interesting result in our work relevant to image coding is the paper by Klein & Beutter (1992, reference #7) because it has caused a stir in several fields. In image compression (and image processing in general) one wants to use filters that are localized in both space and spatial frequency. Gabor once made a claim that for real-valued functions, the Hermite functions (Hermite polynomials times a Gaussian) minimize the joint space-spatial frequency uncertainty. What we showed was that for the class of functions that are an mth order polynomial times a Gaussian, the Hermite functions *maximize* the joint uncertainty. Individuals from different disciplines have indicated the usefulness of this result (e.g. I have been informed that Hermite functions characterize the profile of laser beams and based on Gabor's work it had been thought (before our paper) that this was a *good* profile).

The applied vision field of image compression and image quality is moving extremely rapidly in the engineering community. It is simply shocking to me to see how little research in this area is being done by vision researchers, who have some understanding of underlying mechanisms. We intend to submit a proposal to AFOSR to continue the work we have started in this field.

2) Vernier acuity and modeling. Using the test-pedestal paradigm, we initially established a connection between vernier acuity and contrast discrimination using sinusoidal stimuli (Hu, Klein & Carney, 1992, reference #19). Rather than using a complex model with many assumptions we showed that to first order, vernier acuity was well predicted by contrast discrimination thresholds when both tasks are expressed in the same contrast units. These results can be explained by both tasks using common underlying mechanisms. However several notable exceptions were evident. At high spatial frequencies vernier thresholds degraded faster than expected when compared to contrast discrimination data. Moreover, the tvi slope was always shallower for the vernier task. We have been exploring other stimulus configurations including different line lengths and central gaps in both tasks to determine the source of the deviations from predictions based on contrast discrimination. At high spatial frequencies, decreasing grating length hurt contrast discrimination thresholds but actually improved vernier acuity. The vernier task is presumably performed by oriented mechanisms, the long grating possibly diluted or smeared out the orientation cue which reduced the effectiveness of oriented mechanisms. The difference in tvi slope is likely due to the use of oriented mechanisms. If vernier acuity involves mechanisms oriented away from the pedestal orientation it would avoid some of the contrast masking effects observed for the contrast discrimination task, thereby resulting in a different tvi slope. Further details on this research is provided in the following two ARVO abstracts.

COMPARISON OF GRATING VERNIER ACUITY AND CONTRAST DISCRIMINATION (ARVO 1990)

A test-pedestal approach, in which a test grating was superimposed on a masking pedestal, was used to compare sinusoidal grating vernier acuity and contrast discrimination thresholds. In the contrast discrimination task, subjects were asked to detect contrast increments ($\Delta C \cos fx$) in the presence of a base contrast ($C \cos fx$). In the vernier task, a test grating ($\Delta C \sin(fx+\phi/2)$) was added to one half of the pedestal grating ($C \cos fx$) to produce a vernier offset (δ). The relationship between contrast increment (ΔC) and vernier offset (δ) is given by: $\Delta C = 2C \sin(\phi/2)$ in which phase shift (ϕ) equals $2\pi f d$. Thresholds ($d'=1$) were determined by a self-paced method of constant stimuli with multiple responses. For contrasts below 10 times detection threshold, $R_{VC} > 1$ across all spatial frequencies (where R_{VC} is the ratio of the vernier threshold to the contrast discrimination threshold expressed in % contrast, ΔC), and R_{VC} increased with increasing spatial frequency. At a spatial frequency of 2 c/d, there was a cross-over between vernier and contrast discrimination thresholds as a function of pedestal contrast: at contrasts below about 10 times detection thresholds, $R_{VC} \approx 2$, for contrasts above that, $R_{VC} \approx 0.5$. At high spatial frequency (20 c/d), R_{VC} is about 10 across all pedestal contrasts. At spatial frequencies between 5 to 10 c/d, for contrast above 10 times detection threshold, $R_{VC} \approx 1$. Thus, under these conditions, contrast discrimination predicts grating vernier acuity. A hypothesis that the same mechanism is involved in performing these two tasks at intermediate spatial frequencies will be discussed.

PREDICTING GRATING VERNIER ACUITY FROM CONTRAST DISCRIMINATION: THE EFFECT OF GRATING LENGTH (ARVO 1991)

Last year, we used a test-pedestal approach, in which a test grating was superimposed on a masking pedestal, to compare sinusoidal grating vernier acuity (in contrast units) and contrast discrimination thresholds. We found that grating contrast discrimination thresholds are in good agreement (within 30%) with vernier acuity at spatial frequencies between 5 and 10 c/deg. However, at high spatial frequencies (20 c/degree), vernier thresholds are about 10 times that of contrast discrimination at all pedestal contrasts. We wonder whether shortening the length of the grating may increase the relative effectiveness of the optimal mechanism to perform the vernier task at high spatial frequencies. To test this hypothesis, the same approach was used to measure the grating vernier and contrast discrimination thresholds at various grating lengths at a pedestal contrast of nine times detection threshold at spatial frequencies of 10 and 20 c/deg. At 10 c/deg, vernier threshold increases as grating length is shortened, similar to contrast discrimination. But at 20 c/deg, vernier threshold does not vary much with the grating length while contrast discrimination thresholds increase with decreasing grating length. Thus, when thresholds are plotted as a function of grating length, contrast discrimination and vernier functions intersect at a grating length of 2 minutes for 20 c/deg gratings.

We are now also comparing vernier acuity and grating detection thresholds in the presence of oriented masking gratings [17]. The masks have large effects at orientations somewhat different from the vernier target grating. This masking effect is greatly reduced in the grating detection task. In summary, vernier acuity for the most part is well predicted by contrast discrimination. Future models of vernier acuity will have to consider properties of later stages of processing in order to account for performance where contrast discrimination does not predict vernier acuity. Such models will likely include multiple mechanisms at different spatial scales, orientations, and densities.

We have spent some time working with various modeling tools, such as the early vision emulation software (EVE), Mathematica and Matlab, but have found each lacking in ease of use or flexibility. Our frustration with these tools lead to regular meetings with several other UCBerkeley faculty members discussing the requirements for a powerful vision modeling environment. A group of us (Malik, Banks, Schor, Feldman, Treisman, and Klein) have recently submitted a computational/biological vision proposal to AFOSR. One aspect of this proposal is to develop a user-friendly modeling environment that could be used by the larger vision community. Such a tool would prove invaluable in extending our understanding of spatial and temporal vision.

3) Mechanisms involved in motion processing.

We have carried out a number of studies that are designed to clarify the mechanisms that underlie motion perception. Thom Carney has written up several of these studies [6, 12, 20] and they are included with this report, so they will not be discussed further. The manuscripts for two further studies that were reported by Amnon Silverstein at ARVO are nearly completed. The first study examines the mechanisms underlying our ability to make good vernier judgments for moving stimuli [22]. We provide evidence that the task is accomplished by oriented mechanisms. Also we are developing a simple model that is able to account for the data. A brief summary of this research is provided by the following ARVO abstract:

VERNIER ACUITY DURING IMAGE ROTATION AND TRANSLATION (ARVO, 1990)

It has been proposed that vernier acuity thresholds are achieved by means of an orientation cue. Since the orientation information is constant during translational motion, this model is consistent with the remarkable fact that vernier acuity is unaffected by image motion at velocities less than 2.5°/s. (Westheimer and McKee 1975). However, such a mechanism would be strongly affected by rapid changes in orientation. Using a three dot vernier acuity task with a 0.2 s presentation, we have assessed performance during image translation and rotation. In addition to velocity, we varied luminance and the separation between the dots. We found that, while low luminance elevated thresholds to linear targets, luminance has relatively little effect on thresholds to rotatory targets. Thresholds to linearly translating targets were compared with rotating targets of equal tangential velocity. As expected, linear translational motion did not elevate thresholds. However, rotational motion quickly degraded vernier acuity. Thresholds became elevated with as little as 0.3°/s tangential velocity, an order of magnitude slower than the linear case. These facts are consistent with a model of vernier acuity which emphasizes the use of orientation cues.

Westheimer, G. and McKee, S.P. (1975) Visual acuity in the presence of retinal image motion. J. Opt. Soc. Am. **65** 847-850

The second study [23] examines the rate at which relative motion can be judged. This is closely related to the question of what are the temporal constraints on the "binding problem". Suppose an object consisting of several dots is vibrating rapidly in sinusoidal oscillation. We are interested in what is the highest temporal frequency for which the object can be perceived as rigid. These results will provide constraints on models of object recognition. The following ARVO abstract summarizes this research.

RELATIVE MOTION DISCRIMINATION (ARVO, 1991)

Motion of very small amplitudes (5 sec or less) can be detected when the frequency of motion is optimal (2-4 Hz.) (Tyler and Torres 1972). Previous research has shown that under some conditions, relative motion can be discriminated whenever motion can be detected at all (Mowafy, Lappin, Anderson, and Mauk 1991). In this experiment, we determined the range of frequencies over which this relationship holds. We used two sinusoidally oscillating dots to determine the temporal frequency response function of relative motion discrimination. The subject was presented with two dots that either oscillated inphase (the dots moved in the same direction) or in counterphase (the dots moved in opposite directions). The subject was required to discriminate between the two types of motion for a range of temporal frequencies. When the temporal frequency of the presented stimuli is optimal (~4 Hz), the visual system is remarkably adept at discriminating relative motion. However, a temporal frequency of as low as 8 Hz degrades thresholds and 12 Hz increases them by a factor of 5.33 ± 1.33.

An important new development for my group is that Tina Beard has just joined us. We look forward to many years of fruitful collaboration. This collaboration began this past year while she was in Houston with Dennis Levi and we worked on the following project together. We were interested in the dynamics of the localization process as is described in the following abstract:

SPATIOTEMPORAL PROPERTIES OF LOCALIZATION MECHANISMS (ARVO, 1992)

Localization judgments for two abutting lines are thought to reflect the responses of orientation tuned filters sensitive to both stimuli; however, when the two lines are widely separated in space, position is thought to be coded by local sign mechanisms. The temporal dependence between reference and test lines is not known. We measured localization thresholds across various interstimulus intervals (ISIs) for abutting and spatially separated reference and test lines at set contrasts above detection threshold. The lines were presented on a uniform field with a mean luminance of 132 cd/m^2, for a duration of 150 msec. Observers discriminated the direction and amount of offset between the reference and test lines using a 5 alternative rating scale. As expected based on Weber's Law, threshold increased proportionally with the spatial separation of the two simultaneously presented lines. For abutting lines, thresholds increased dramatically with even a very brief (3.5 msec) ISI, perhaps due to masking (Westheimer and Hauske, 1975). For wide spatial separations (e.g., 90 min), localization thresholds were independent of ISI. We can rule out edge artifacts or unwanted position cues since thresholds for widely separated targets were independent of viewing distance. Our results are consistent with the notion that the precision of spatial localization is constrained by different mechanisms when the target lines are abutting, and when they are well separated. The most precise localization thresholds occur when the target lines are presented in close spatial and temporal proximity as might be expected from the response of a single filter sensitive to the contrast of both lines; for widely separated targets, thresholds are virtually independent of ISI, consistent with a local sign mechanism in which the two lines are processed by separate filters, and their position labels compared.

We believe that models of motion processing are still in a very immature stage. Most present models are satisfied with qualitative agreement with data rather than quantitative agreement. We intend to improve on these models over the next few years.

4) Connecting psychophysics to physiology: The visual evoked potential.

One of our goals is to connect our psychophysics experiments to physiology. My graduate student Heidi Baseler is doing her doctoral disseration on Visual Evoked Potentials (VEP). Although she is not being supported by AFOSR, I consider a small amount of time I have spent on this project to be AFOSR supported and we are citing AFOSR support in all of our publications. One of our goals is to use the stimuli of our AFOSR psychophysics research in our VEP studies.

4a) The test-pedestal approach. The power of the test-pedestal approach for revealing underlying mechanisms in our psychophysical studies led us to record visual evoked potentials (EP) to similar stimuli with the goal of cortical functional localization. The temporally varying test pattern was identical across conditions, the different static pedestal patterns determined the stimulus condition: dynamic vernier, motion, contrast modulation or counterphase sinewave. This approach has the advantage that the test signal that generates the EP was identical across conditions. The results were compatible with psychophysical results described above but functional localization was not possible with the limited number of recording channels available to us. A summary of this work is contained in the following ARVO abstract.

A TEST-PEDESTAL PARADIGM FOR USE WITH VISUAL EVOKED POTENTIALS (ARVO, 1990)

The visual evoked potential (EP) to a temporally modulated test grating was evaluated in the presence of a variety of static pedestal gratings. The test pattern was always: $\Delta C \cos(fy)*\cos(\omega t)$. The pedestal gratings were chosen such that the phenomenal appearance of the stimuli included a moving vernier, a jittering grating, two types of contrast modulation and a counterphase grating.

The stimulus field was divided into left and right halves which contained the horizontal gratings. The pedestal gratings utilized to generate the stimuli described include:

Left Half	Right Half	Appearance
Blank	(C+ΔC) cosfy + test	Contrast Modulation.
C cosfy	(C+ΔC) cosfy + test	Contrast Modulation, appearance-disappearance
Blank	(C+ΔC) sinfy + test	Up and down motion of sinewave.
C cosfy	(C+ΔC) sinfy + test	Dynamic vernier, appearance-disappearance.
Blank	Blank + test	Counterphased sinewave.

This approach has the advantage that the temporally modulated signal generating the EP is constant across conditions. Any condition dependent changes in the EP results from pedestal difference which don't by themselves produce an EP. This provides a convenient means for comparing diverse perceptual tasks as well as determining the effects of pedestal intensity on the EP to a common test pattern. The relative strengths of the fundamental frequency and the second harmonic components of the EP were compared across tasks. In the presence of pedestal, the overall amplitude of the EP at the second harmonic decreased for all conditions. The masking as a function of pedestal strength compare well with psychophysical results on these types of tasks.

4b) Topography of diverse stimuli. More recently we teamed up with Anthony Norcia and Peter Wong (ARVO 1991) who had collected EPs to a variety of stimulus categories, vernier jitter, color, onset/offset, and counterphase patterns using a 21 electrode recording array. Our analysis of the data revealed some cortical specificity for the type of stimulus pattern. Unfortunately, the stimuli were not selected according to the test-pedestal paradigm which complicated comparisons across stimulus conditions. A summary of this research is presented in the following ARVO abstract:

VEP TOPOGRAPHY OF PERCEPTUALLY DIVERSE STIMULI (ARVO 1991)

Technological advances in computer mapping programs and statistical analysis methods have made VEPs an increasingly sensitive and convenient technique for localizing cortical function. By selecting visual stimuli that vary along distinct perceptual dimensions, we can compare the scalp topography of such visually diverse phenomena as pattern onset/offset, counterphase, vernier, jitter, temporal frequency and color. Ten different steady-state stimuli were presented to 14 normal subjects whose VEPs were recorded from 21 electrode sites. In all cases, the stimuli were vertically oriented, 2 c/deg square wave gratings, undergoing square wave temporal modulation. Stimuli varied as follows: pattern onset/offset and counterphase of luminance and isoluminant color gratings, counterphase and jitter at 3 and 10 Hz, symmetric dynamic vernier (90^{o} phase shift in both directions) and asymmetric dynamic vernier (180^{o} phase shift in one direction). Condition-specific differences were found in signal magnitude and distribution. Fourier analysis revealed a strong response at all even harmonics to the jitter, counterphase and symmetric vernier stimuli, whereas the onset/offset and asymmetric vernier stimuli had peaks at both odd and even harmonics. Occipital sites showed the greatest activity in all conditions, as expected from a visual task. Of greater interest was the relative differences in activity in the temporal, parietal and central electrodes between conditions. In particular, the pattern onset/offset and asymmetric vernier stimuli generated significant activity in the central electrodes relative to the counterphase and symmetric vernier conditions. Further conditional differences were found and will be discussed in more detail.

Articles: Published and In Press (January 1, 1989 - July 31, 1992).

I have enclosed one copy of each of the articles not submitted with previous Annual Technical Reports (or those for which preliminary versions were sent). All of the following papers cite AFOSR for their support. Please let me know if you are missing any of them and I'd be most happy to send another copy.

1. Klein, S. A. (1990). High resolution and image compression using the discrete cosine transform. *SPIE: Human Vision and Electronic Imaging, Methods and Application.* **1249**, 135-146.
2. Klein, S. A. and Carney, T. (1990). How many bits/min^2 are needed for the perfect display? *Society for Informational Display 90 Digest* **21**, 456-459.
3. Klein, S. A., Casson, E, and Carney, T. (1990). Vernier acuity as line and dipole detection. *Vision Res.* **30**, 1703-1719.
4. Klein, S. A. & Carney, T. (1991). "Perfect" displays and "perfect" image compression in space and time. *Human Vision, Visual Processing and Digital Display II.* Bernice E. Rogowitz, Jan P. Allebach and Michael Brill, Editors, Proc. **SPIE 1453**, 190 - 204.
5. Klein, S. A. & Carney, T. (1991). How the number of required gray levels depends on the gamma of the display. *Society for Informational Display 91 Digest* **22**, 623-626.
6. Carney, T. & Shadlen, M. N. (1992). Binocularity of early motion mechanisms: comments on Georgeson and Shackleton. *Vision Research* **32**, 187-191.
7. Klein, S. A. & Beutter, B. (1992). Minimizing and maximizing the joint space-spatial frequency uncertainty of Gabor-like functions. *J. Opt. Soc. Am. A.* **9**, 337-340.
8. Klein, S. A. (1992). Optimizing the estimation of nonlinear kernels. *Nonlinear Vision.* Eds. Robert B. Pinter and Bahram Nabet. CRC Press. 109 - 170.
9. Klein, S. A. (1992). Channels: Bandwidth, channel independence, detection vs. discrimination. Chapter in Channels in the visual nervous system: Neurophysiology, psychophysics and models. Blum, ed. 11 - 27.
10. Klein, S. A. (1992). An EXCEL macro for averaging data. *Behavior Research Methods, Instruments, & Computers* **24**, 90-96.
11. Hu, Q., Klein, S. A., & Carney, T. (1992). Temporal luminance masking in the coding of video signals. *Society for Informational Display 92 Digest* **23**, 255 - 258.
12. Carney, T., Schor, C., Steinman, S. & Wilson, N. (1992). Assessment of binocular integration in amblyopia using a motion stimulus. In Noninvasive Assessment of the Visual System Technical Digest, 1992 (Optical Society of America, Washington, D.C.) Vol. 1, 64-67.
13. Klein, S. A. & Tyler, C. W. (1992). The psychophysics of visual detection: A review of Graham's "Visual Pattern Analyzers". (In press, *Journal of Mathematical Psychology*).
14. Klein, S. A. (1992). Image quality and image compression: A psychophysicist's viewpoint. (In press, chapter in Visual Factors in Electronic Image Communications, MIT Press).
15. Klein, S. A. (1992). Spatial vision models: Problems and successes. (In press, chapter in Spatial Vision in Humans and Robots, Cambridge University Press).
16. Klein, S. A. (1992). Will robots see? (In press, chapter in Spatial Vision in Humans and Robots, Cambridge University Press).
17. Waugh, S. J., Levi, D. M. & Carney, T. (1992). Orientation, masking and vernier acuity for line targets. (Vision Research, In Press).
18. Klein, S. A., Silverstein, D.A. & Carney, T. (1992). Relevance of human vision to JPEG-DCT compression. (In press, *Human Vision, Visual Processing and Digital Display III.* Bernice E. Rogowitz, Jan P. Allebach and Stanley A. Klein, Editors, Proc. **SPIE 1666**.)

Articles: Submitted.

19. Hu, Q., Klein, S. A. & Carney, T. (1992) Can sinusoidal Vernier acuity be predicted by contrast discrimination? Almost. (Submitted to Vision Research).

20. Carney, T. & Shadlen, M. (1992). Dichoptic activation of the early motion system. (Submitted to Vision Research.)

21. Klein, S. A. (1992). Inverting a Laplacian topography map. (Submitted to Brain Topography).

Articles: In Preparation. These are articles that we plan to complete before we submit our proposal to AFOSR. All of these articles were supported solely by this AFOSR grant except for Sutter's support.

22. Carney, T., Silverstein, D. A. & Klein, S. A. (1993). Vernier acuity during image rotation and translation: Visual performance limits. (To be submitted to Vision Research).

23. Silverstein, D. A. & Klein, S. A. (1993). Discrimination of relative motion. (To be submitted to Vision Research).

24. Beard, T., Klein, S. A. & Carney, T. (1993). The detection and discrimination of flicker and jitter in human vision. (To be submitted to Vision Research).

25. Baseler, H., Sutter, E., Klein, S. A. & Carney, T. (1993). The visual evoked potential and multi-input stimulation. (To be submitted to Brain Topography).

26. Hu, Q. & Klein, S. A. (1993). Crawford masking for light and dark lines: The effect of spatial proximity. (To be submitted to Vision Research).

Presentations at ARVO and OSA

ARVO (Association for research in Vision and Ophthalmology)

1990 Hu, Q., Klein, S. A. and Carney, T. "Comparison of grating vernier acuity and contrast discrimination."

1990 Silverstein, D. A., Carney, T. and Klein, S. A. "Vernier acuity during image rotation and translation."

1990 Baseler, H., Carney, T. and Klein, S. A. "A test-pedestal paradigm for use with visual evoked potentials."

1991 Silverstein, D. A., Klein, S. A. and Carney, T. "The detection of temporal asynchrony in two-dot targets."

1991 Hu, Q., Klein, S. A. and Carney, T. "Predicting grating vernier acuity from contrast discrimination: the effect of grating length."

1991 Baseler, H., Norcia, A. M., Wong, P., Carney, T. and Klein, S. A. "VEP topography of perceptually diverse stimuli."

1991 Carney, T. and Klein, S. A. "Orientation masking of grating vernier acuity".

1992 Beard, B., Levi, D. M. and Klein, S. A. "Spatiotemporal properties of localization mechanisms."

1992 Hu, Q., Klein, S. A. and Carney, T. "Line detection under temporal masking."

1992 Klein, S. A., Levi, D. M., and Wang, H. "The visibility of sampled gratings."

OSA (Optical Society of America)

1990 Levi, D. M., Klein, S. A. and Wang, H., "How many samples are needed for precise localization?"

1990 Klein, S. A., Carney, T. and Levi, D. M., "The dependence of vernier acuity on blur".

1991 Klein, S. A. and Beutter, B. "Hermite functions maximize the space-spatial frequency uncertainty of Gaborlike functions."

1991 Silverstein, A. D.and Klein, S. A. "Relative motion discrimination.

List of professional personnel on the project

Stanley A. Klein, Principal Investigator, Thom Carney, Associate Research Specialist

Heidi Baseler, Qingmin Hu, Amnon Silverstein graduate students